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Effect of dust pollutant type on photovoltaic performance

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ABSTRACT

Many environmental parameters affect the production of photovoltaic (PV) systems and dust could be one of the main reasons of degradation of PV panels. PV systems utilized in large and small scales accumulate different types of dust which reduce the efficiency. The dust contents, which represent a mixture of different pollutants, are specified by the geographical site. There are many studies focused on the effect of dust on PV performance but few studies have investigated the effect of dust pollutant type on the performance. Mainly, the effect of pollutant type has been investigated indoors and few outdoors. In the present paper the effects of pollutant types on the PV performance have been revised and experimented. A critical review and challenging questions have been developed for the researchers working in this field.

Contents

1. Introduction

Due to the fast development in economical and technological aspects, solar photovoltaic PV industry has been disbursed globally. As a result of this development, the consumption of energy is increasing dramatically yearly because of development, demand of comfort and the growth of the world population [1]. Electricity is mainly generated by the use of a variety of sources such as fossil fuels which play a vital role in meeting the demand for energy. The impact of greenhouse gases (GHG) on the environment and global warming is enormous and arduous on the people. A suitable solution to reduce these effects and save the environment is the use of solar PV as a renewable energy source.

In a PV, the sun light energy is absorbed by the semiconductors as photons after which they are converted into a voltage. The design of these solar-energy systems covers a set of wide-ranging materials science and engineering, as well as innovative approaches to lowering cost and increasing system performance [2]. In 1960, researchers conducted experiments on semiconductors (III–V and VI) while a new technology for polycrystalline Si (pc-Si) and thin film solar cell was established in order to lower the materials cost and energy input but increase the production capacity.

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In addition to the investment of money and time in the development of materials used in the production of solar cells, there are many factors which need to be investigated and understood. For example dust pollutant types need to be investigated as they have not been studied intensively. Dust is defined as any particulate matter less than 500 μm in diameter, which enters the atmosphere from different sources such as dust lifted by wind, vehicular exhaust, volcanic eruptions and air pollution. Dust may contain small amounts of pollen and also fungi, bacteria, vegetation, microfibers, and, most commonly, organic minerals such as sand, clay, and eroded limestone [3].

The dust pollution effect strongly depends on the local area where the PV system is mounted, so it is difficult to apply a general model in all cases [4].In urban and other environments many types of pollution emitted from different sources can be faced. For example limestone is formed from precipitation of calcium carbonate ($CaCO_3$), ash is emitted from vehicular exhaust while red soil is moved from African deserts. Monto and Rohit have revised the effect of dust on PV performance based on two time periods: 1940–1990 and 1990–2010, and the authors have discussed the effect dust properties based on three main points: effect of dust properties, effect of PV system parameters and effects of environmental parameters [5–7]. A comprehensive review of dust effect on the use of solar systems was presented by Travis Sarver et al. [2]. This research aims to characterize the deposition of dust (pollutant type) and their effect on PV system performance. It is worth mentioning that pollution deposition is a difficult phenomenon influenced by diverse site-specific environments and weather conditions. In this paper the effect of dust pollutant type has been revised. The effect of different pollutant types on current, voltage, power and efficiency has been discussed. Finally, a comparison between different pollutants in term of effect on PV current, voltage, efficiency, power, etc. is presented.

2. Position of dust-pollutant type problem

Dust pollution is composed of small solid particles carried by the air currents. These particles are formed by a variety of ways, such as breakage of the solids into small pieces, by means of milling or other ways. The Mine Safety and Health Administration (MSHA) has defined dust as finely divided solids that are in air from the initial state, without chemical or physical changes other than fracture. Dust particle size is generally measured in micrometers. The thickness of dust on the solar panel increases with time [8].

The effect of dust on PV performance is investigated by many studies. The factors which determine the dust accumulation characteristics of PV systems are the materials properties and the local environment [9–13]. The environment consists of the local site-specific factors which are influenced by the natural human activities, built environment characteristics (surface finish, orientation and the installation height), ecological factors and the weather conditions [5].

The properties of dust, which include chemical, biological, electrostatic, shape, size and weight, are very important in its accumulation. Although the PV energy lost due to dust pollution is of great interest to PV system owners and operators, there are few studies presented concerning the dust pollutant types. Much of the information available is valid only to the specific location in which the testing was conducted. For example in Greece many experiments were conducted by Kaldellis to evaluate the effect of different pollutions (ash, calcium carbonate, red soil) on PV performance [14,15] while Hussein used the same pollution but added sand and silica [16,17]. On the other hand in the analysis of dust sand collected from module surface in the United States and the MENA regions in Egypt, it was found that the major components are quartz silicates (SiO_2), about 75%; and feldspars ($NaAlSi_3O_8$, $CaAlSi_3O_8$, $KAlSi_3O_3$), about 20% [2,18]. Fig. 1 shows the result of X-ray diffraction (XRD) analysis to identify the chemical composition of dust layers where it is found that the major elements are silicon from desert sand (quartz, or silicon dioxide, SiO2) and calcium from the mineral calcite (calcium carbonate, $CaCO_3$): minor elements included iron, potassium, aluminum, and sodium.

The largest global source of atmospherically transported desert is in North African countries. Sarah conducted an extensive study about dust deposition for 1 year in different zones across Libya. It was found that Libya has the highest deposition rate in North Africa. The mineral composition of sediment collected includes halite (NaCl), chlorite ($MgFeAl_2(OH)$), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), feldspar ($KAlSiO_3O_8$), quartz (SiO_2), and albite ($NaAlSi_3O_8$) [19].

The effect of air pollution is serious in urban areas due to the high population density and growth in the industrial activities [20], specifically dust and particles which are produced by the combustion of fossil fuels and construction activities. Deposition in the front of the PV panels can significantly reduce the amount of solar energy eventually absorbed by the PV. Therefore, an important change in PV panels' output voltage and current is expected due to the PV's remarkable performance degradation.

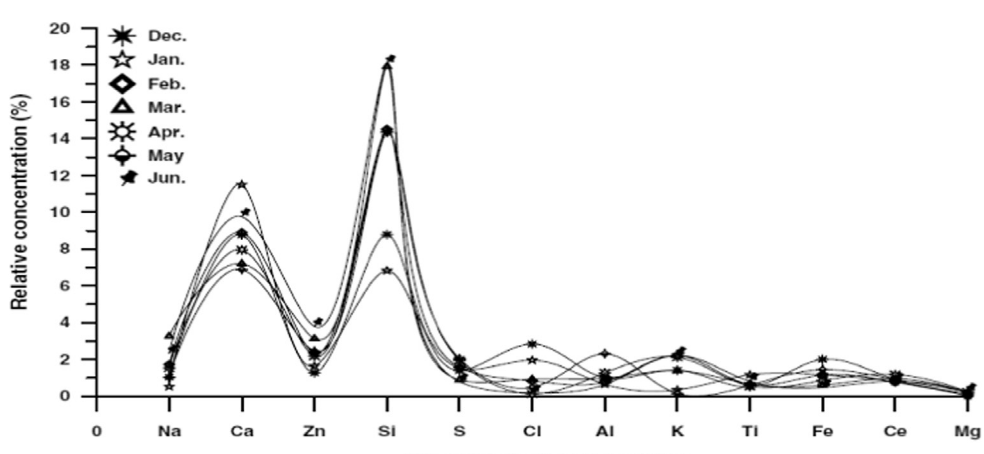

Fig. 1. X-ray diffraction analysis of the polluting material [18].

3. Effect of dust pollutant type

The first point to be investigated is the effect of dust properties on the PV system. Most of the studies have investigated factors influencing dust settlement such as wind velocities, dust properties, glazing characteristics. PV system installation and environment characteristics like ambient temperature and humidity have been overlooked in the effect of the type pollution. Few studies have pointed to the type of dust and chemical composition.

Table 1 provides an overview of the researchers who studied dust pollutant types. The table is based on a database of different types of pollutions which are used in experiments, and three types of experiments are summarized. First experiments were conducted in open space (outdoor) and relied on the accumulation of natural dust on PV cells and analyzed after the end of the experimental period [23–32]. Secondly, the experiments had been conducted in a laboratory and used artificial pollutants as e.g. carbon (5 μm), cement (10 μm), limestone (50, 60, and 80 μm), and fine and coarser dust [33,34].

Finally the experiments were conducted indoors to simulate dust (artificial) and used mud, talcum, red soil, fly-ash, sand, calcium carbonate, silica and test dust (ISO 12103-1 A2, Powder Technology Inc.) [35–37]. The important observation in this table has led us to a critical point that the pollutants mentioned in the table do not cover large areas of the world which in fact vary from one area to another. To prove this point the authors have collected the dust accumulated on a horizontal glass surface for the period from the beginning of September 2013 to the end of December 2013 from various sites in the United Arab Emirates: Sites I and II are located in Wadi Al Helo which lies near the border of Oman. Site I is an agricultural area relying on water wells (salty water) while the second area depends on clean water free of salt (no salt water). The third area (Site III) is located on the desert road between the cities Fujairah and Sharjah. The fourth area (Site IV) is located on the Coast of the Arabian Sea in the city of Fujairah. Mineralogical analyses of dust particulates collected on glass cups have been performed by X-ray diffraction (XRD) (Bruker D8 Advance) and X-Ray Fluorescence (XRF) (Horiba XGT-7200) to provide qualitative and quantitative materials characterization for detection and analysis. The main results obtained from the study XRF are reported in Table 2.

It was found that there are 14 compounds contained in the four dust samples with different ratios depending on the location. The compounds are MgO, Al_2O_3, SiO_2, SiO_3, K_2O, CaO, TiO_2, Cr_2O_3,

Table 1
Studies of selected investigation of dust pollutants.

Authors/reference	Year	Location	Type	Composition/name/chemistry	Type of solar technology
Niknia [24]	2012	Iran/outdoor	Natural	Sand particle	Solar collector
Sergy Biryukov [25]	1997	Israel /outdoor	Natural	Coarser mode of airborne dust	Mirror surface
Kaldellis and Fragos [14]	2011	Greece/indoor	Artificial	Ash	PV system
Cabanillas and Munguía [26]	2011	Mexico	Natural	Natural of dust in atmosphere	PV system
Geoffrey A. Ludis [27]	1995	USA	Natural	TSP in MARS data from NASA	
Adel A. Hegazy [12]	2000	Egypt/outdoor	Natural	Suspended dust	Glass plate
Mastekayeva and Kumar [40]	1999	Thailand	Natural	Natural dust	Solar air heater
Shaharin A. Sulaiman [35]	2011	Malaysia/indoor	Artificial	Mud and talcum	PV system
Md.Mizanur Rahman [8]	2012	Bangladesh/outdoor	Natural	Natural dust	PV system
Hai Jian [36]	2011	China/indoor	Artificial	Test dust (ISO 12103-1 A2, Powder Technology Inc.) SiO_2 (68–76.9%), Al_2O_3 (10–15%), Fe_2O_3 (2–5%), Na_2O (2–4%), CaO (2–5%), MgO (1–2%), TiO_2 (0.5–1%), K_2O (2–5%)	PV system
Kaldellis and Kapsali [4]	2011	Greece/indoor	Artificial	Ash less 10 μm, Limestone less 60micron, Red soil less 150micron	PV system
Reinhart Appels1 [38]	2012	Belgium/indoor	Natural	Natural examine by SEM contain artificially contaminated (sand (250 μm), clay (68 μm) and cement (10 μm))	Normal glass
Huey Pang [32]	2006	China/outdoor	Natural	General air pollution, refer to resource carbon-fuel based electricity-generation, factory and vehicle emissions	Commercial copper Indium Diselenide modules
Pavan et al. [41]	2011	Italy/outdoor	Natural	Sand soil	PV system
Sanusi [28]	2012	Nigeria/outdoor	Natural	Harmattan dust (December, January and February)	PV system
Al-Soleimani [29]	2001	Iran/outdoor	Natural	Air pollution	PV system
Kaldellis and A. Kokala [31,32]	2010	Greece/outdoor	Natural	Urban air pollution(densely populated)	PV system
E. Suresh Kumar [37]	2013	India/indoor	Artificial	Used clay and refer to natural dust chemical composition of natural dust which are basically SiO_2 and Al_2O_2	PV system
Abd Salam AI-Ammri [39]	2013	Iraq/outdoor	Natural	SiO_2, $CaCO_2$, Gibson ($CaSO_4 \cdot 2H_2O$), Dolomite ($CaMg(CO_3)_2$), Anorthite ($CaAl_2Si_2O_8$), Kaolinite ($Al_2Si_2O_5(OH)_4$),Ti, Cr, Mn, Fe and Cu	PV system
Elminir et al.[18]	2006	Egypt	Natural	Quartz silicates (SiO_2), about 75%; and feldspars ($NaAlSi_3O_8$, $KAlSi_3O_8$, $CaAl_2Si_2O_8$) about 20%.	Solar collector
Elshobokshy [33]	1993	K. Sudia/indoor	Artificial	The experimental dust was prepared from limestone rocks containing the minerals calcite and silica. ((carbon 5 μm), (cement(10 μm), limestone(50,60,80)μm)	PV system (1 MW)
Elshobokshy [34]	1993	K.Sudia/indoor	Artificial	Fine and coarser dust (size fractions: less than 2.5 μm (fine particles) and 2.5–15 μm)	Photovoltaic concentrators
J. Keller [23]	1995	Alaska/outdoor	Natural	Halite(NaCl), chlorite $MgAl_2(OH)$,Dolomite $CaMg(CO_3)_2$ Calcite $CaCO_3$, Feldspar $KAlSi_3O_8$,Albite $NaAlSi_3O_8$	
Kaldellis [15]	2011	Greece/indoor	Artificial	Red soil, limestone and carbonaceous fly-ash particles	PV system
Hussein A. Kazem [16],[17]	2013	Oman/indoor	Artificial	Red soil, fly-ash,sand, calcium carbonate and silica	PV system
Sarah. L. O'Hara [19]	2006	Libya	Natural	Halite(NaCl),chlorite (Mg Fe $Al_2(OH)$), calcite $CaCO_3$), dolomite ($CaMg(CO_3)_2$),feldspar $KAlSi_3O_8$,quartz SiO_2, and albite $NaAlSi_3O_8$	
A.Benatiallah [21]	2012	Algeria	Natural	-	Multi-crystal solar
H. Haeberlin [22]	1998	Switzerland	Natural	Biological plants(moss, lichen), Iron oxide, an organic components (Mg,Al,Si,P,S,K,Ca,Fe,Cu)	PV system

MnO_2, Fe_2O_3, NiO, SrO, Cl and P_2O_3. Also, it is found that silicon dioxide (SiO_2) is present in greater percentage in all samples at 55.79% followed by calcium oxide (CaO) at 30%. The residual ratios are different in the rest of the material. The XRD characteristic intensities of the dust in the analysis procedure are shown in Fig. 2a–d. In Fig. 2a, calcite ($CaCO_3$) is recognized from the high peak and the second peak is from quartz (SiO_2) while in Fig. 2b and c the quartz has a high peak and the second pollutant is calcite; the samples for three sites contain minerals like Ca, Fe, Mg, Mn, Na, Si and TiO_2. Fig. 2d has more noise and contains more minerals compared with previous figures like (Cl) but with low ratio. In conclusion all types of dust which were collected from different sites have mainly high proportions of quartz and calcite while other minerals are at secondary proportion in terms of the composition of the dust.

4. Effect of pollutant type on current, voltage, efficiency and power

Dust pollution upsets the current and voltage of PV cells due to the prevention of light coming on PV cells. El-Shobokshy and Hussein were amongst the pioneers who investigated the dust properties by simulating the impact of different types dust on the

Table 2
X-ray fluorescence data of dust collected.

Site I	Border of Oman (Salty water)													
	MgO	Al_2O_3	SiO_2	SiO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO_2	Fe_2O_3	NiO	SrO	Cl	P_2O_3
Mass%	6.93	7.91	41.76	2.84	0.79	24.94	0.76	0.45	0.27	12.26	0.11	0.10		0.88
Uncertainty	0.12	0.03	0.02	0.00	0.01	0.06	0.00	0.01	0.01	0.02	0.00	0.00		0.02
Site II	Border of Oman (No salty water)													
	MgO	Al_2O_3	SiO_2	SiO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO_2	Fe_2O_3	NiO	SrO	Cl	P_2O_3
Mass%	6.33	10.83	45.53	0.24	0.87	24.62	0.45	0.23	0.21	10.46	0.09	0.13		
Uncertainty	0.13	0.06	0.01	0.01	0.02	0.07	0.01	0.00	0.00	0.01	0.00	0.00		
Site III	Desert road													
	MgO	Al_2O_3	SiO_2	SiO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO_2	Fe_2O_3	NiO	SrO	Cl	P_2O_3
Mass%	3.99	3.81	55.79	021	1.16	30.40	0.31	0.10	0.07	3.94	0.07	0.12		
Uncertainty	0.04	0.31	0.88	0.01	0.10	0.15	0.13	0.01	0.02	0.20	0.01	0.00		
Site IV	Fujairah city (Coast of Arabian Sea)													
	MgO	Al_2O_3	SiO_2	SiO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO_2	Fe_2O_3	NiO	SrO	Cl	P_2O_3
Mass%	17.37	3.42	38.11	0.56	0.06	21.02	0.35	0.48	0.28	16.68	0.40	0.02	1.07	
Uncertainty	0.15	0.04	0.17	0.02	0.00	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.11	

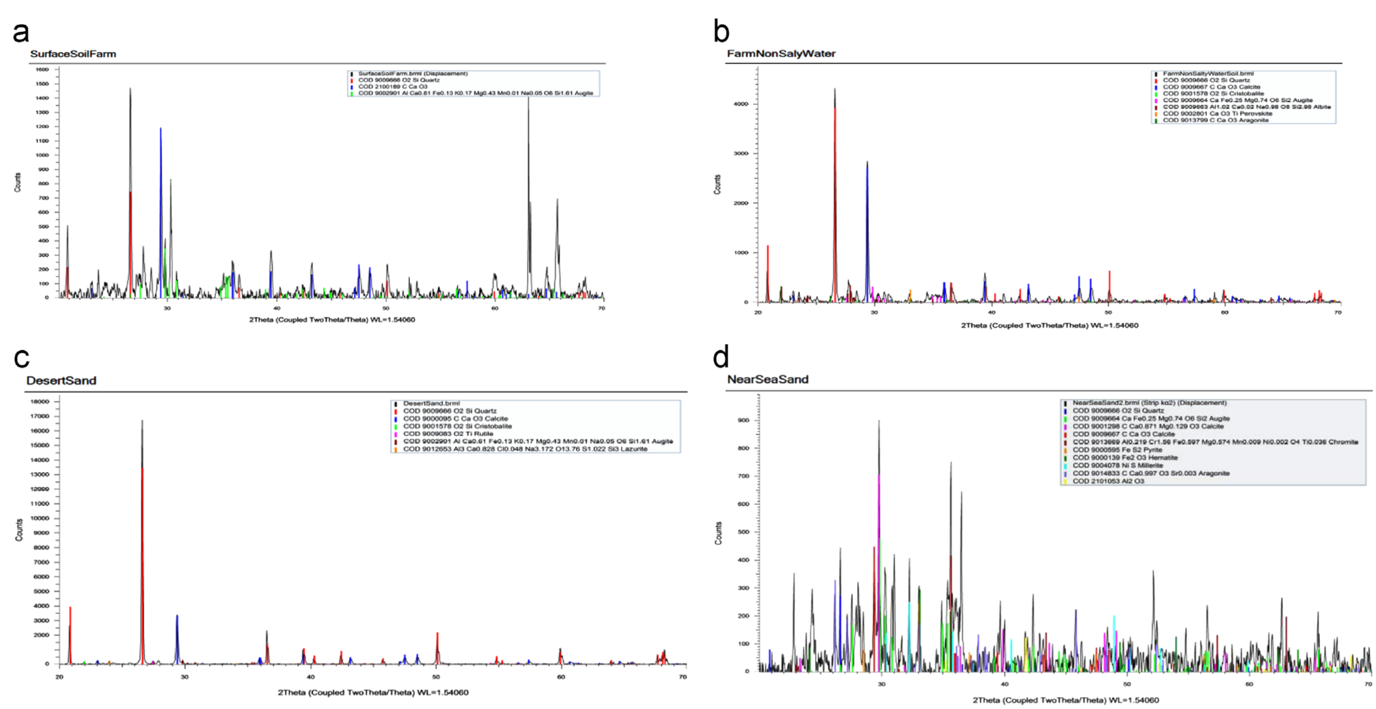

Fig. 2. (a) XRD patterns of dust collected from Site I. (b) XRD patterns of dust collected from Site II. (c) XRD patterns of dust collected from Site III. ***(d)*** XRD patterns of dust collected from Site IV.

performance of the PV panels [33,34].This study which contains five types of dust with different physical properties used three different classes of carbon, cement and limestone. Table 3 evaluates the size distribution of the different types and also shows that the cement and carbon particulates have the lowest standard deviation. This means that the uniformity of particle size is better compared to other dust.

The laboratory experiments which used simulators consisted of three halogen 1000 W lamps. This source provides radiation covering the range of 0.40–4.0 μm, which is enough to simulate the sun. Dry air existed below the dust on the clean panel, and left a sufficient period of time in order to gather dust. The distribution of the dust on the panel was checked by a microscope. Authors used many sponge rubber pieces to determine the mass layer of the dust deposited by wiping the surface by rubber pieces. The sponge rubber pieces were able to remove the dust and to keep the panel clean. The pieces were transferred to a dryer for 24 h to evaporate the water and to confirm that the pieces returned to their primary case where only the particles of dust were stacked to them. The net weight of particles dust was known by the difference between the final and primary weight of the sponge pieces. The operation was repeated. The mass of dust deposition (g/m^2) was measured by dividing the weight of dust by the cleaned area. This operation was repeated many times for numerous densities of type of dust. Four factors were studied as a function of dust deposition namely short-circuit current, power output, reduction in solar intensity and fill factor as shown, respectively, in Figs. 3–6. Figs. 3, and 4 show that the short circuit current and power output have the same result and depict same effects because the change in open voltage circuit is not affected by dust accumulation until the layer of dust blocks light totally. Fig. 5 shows that the particles size of dust deposited and materials affects the PV performance. It is well known that the carbon particulates produced by the burning process absorb the solar radiation very effectively. Fig. 6 indicates the fill factor versus the

Table 3
Outcomes of size distribution analysis of artificial dusts [33].

Dust type	Mean Diameter (μm)	Standard deviation
Limestone		
Grade I	80	1.29
Grade II	60	1.25
Grade III	50	1.28
Cement	10	1.18
Carbon	5	1.136

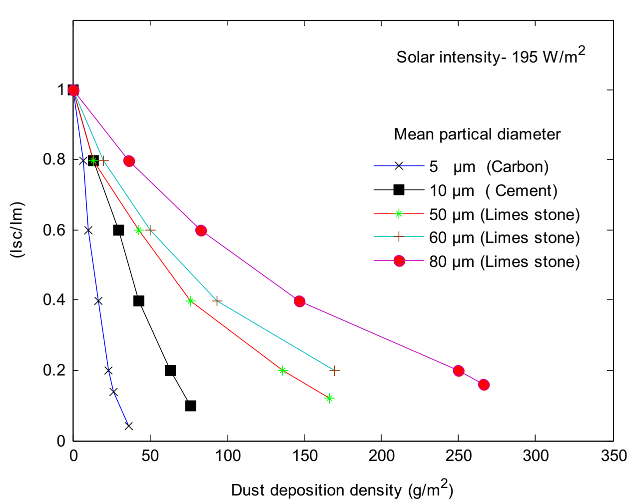

Fig. 3. Different values of short circuit current with dust accumulation density [33].

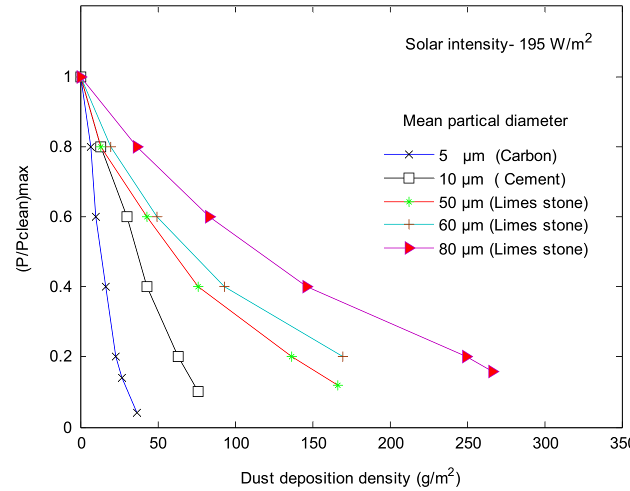

Fig. 4. Different values of power output with dust accumulation [33].

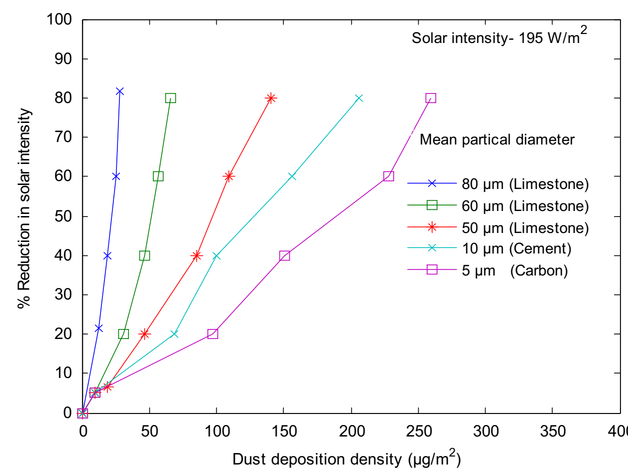

Fig. 5. Decrease in solar intensity delivered to photovoltaic cell with dust accumulation [33].

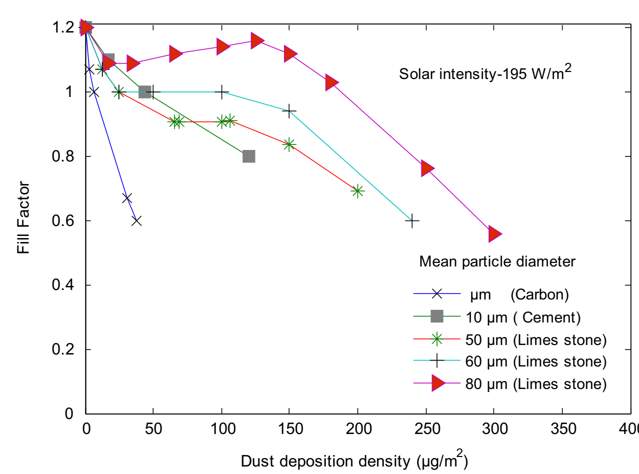

Fig. 6. Different values of fill factor with dust accumulation [33].

deposition density of different dust used. It was found that for cement and carbon it decreased gradually but for the limestone particles greater than (40 g/m^2) it initially decreased and then increased, reaching a maximum value and decreasing with more dust deposition on the PV surface.

Kaldellis et al. [4,15] did a similar study for the different effects of pollution types on the performance of PV cells. They used red

soil, limestone and carbonaceous fly ash particles to investigate the performance of two similar pairs of PV panels. The first panel was cleaned and the second artificial with three types. A systematic experimental study of the pollution deposition was carried out under the same environmental conditions such as ambient temperature, solar, humidity, etc. The study showed that the magnitude of decrease depends on the type of pollution. According to the results of experimental studies, the most significant effect on PV's performance was the red soil accumulation, compared to the limestone and ash. It appears that the produced energy is clearly reduced by red soil deposition on PV's surfaces while the impact is not only slightly smaller for limestone but also significantly smaller for ash. The result indicates that chemical composition, color and diameter range of red soil cause the PV-panel to operate with a lower performance. The results presented in Fig. 7 show that the deposition of each pollutant causes completely different effects on photovoltaic performance. Mainly, a quantity of only 0.35 g/m^2 of red soil may cause the energy production to drop by almost 7.5% while approximately the same deposition density of limestone (0.33 g/m^2) causes almost 4%. For the ash effects, if the mass is doubled to (0.63 g/m^2) the energy produced is reduced by 2.3%. According to their study, Kaldellis and Kapsali [4] developed a mathematical model for dependable analysis results to calculate the exact regional air pollution on PV

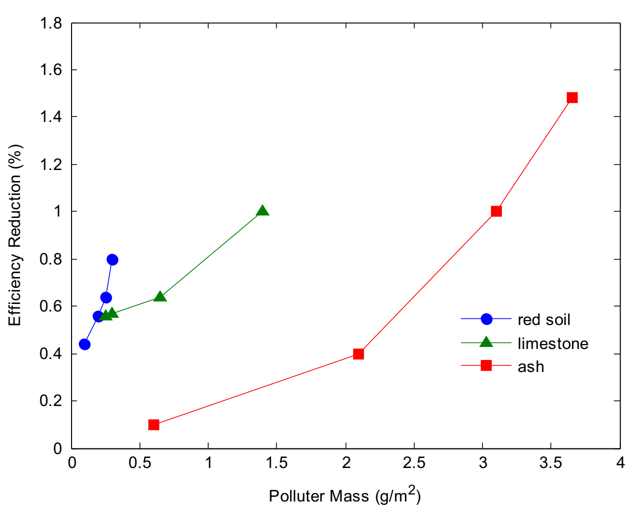

Fig. 7. Efficiency differences between the clean and the polluted pairs panels for various mass depositions of the examined pollutants [4].

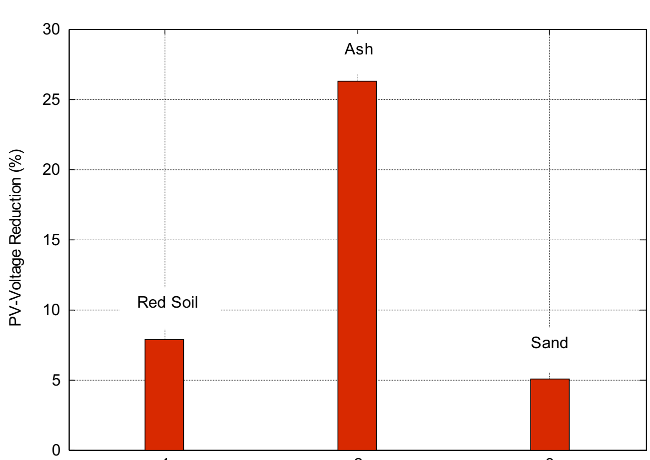

Fig. 8. Reduction in PV voltage due to the three pollutants [16].

performance. Air pollution in this study is represented by red soil, limestone and carbonaceous material.

Kazem et al. [16] have investigated experimentally the impact of three types of dust pollutants (red soil, ash and sand) on the performance of PV panels (mono-c-, multi-c- and a-Si technologies investigated.The authors claimed that ash has the highest effect in comparison with other pollutants. In addition, it is found that a-Si performs better than mono-c- and multi- in dusty environment as in Fig. 8.

In the same context Khatib et al. [17] investigated the dust effect on PV performance by using different types of air pollutants, including red soil, ash, sand, calcium carbonate, and silica. It was found that the PV voltage and power decreased regardless of the type of pollution and deposition level. Fig. 9 illustrates that the worst result is with ash when compared to other pollutants. Ash deposition on PV surface causes larger reduction in voltage, while red soil, calcium carbonate, silica and sand effect come next.

Sulaiman et al. [35] conducted an experiment to study the effect of the dust accumulation on PV performance. Authors used mud and talcum to simulate the dust with constant irradiation. The power generated from PV panel is given in Table 4. It can also be seen that the dust reduces the efficiency of PV panel but the lesser the effect, the more the irradiation level. Figs. 10–12 show *I–V* curves for different cases: clear plastic sheet, plastic dusted with mud, plastic dusted with talcum and solar PV without any plastic sheet for different irradiation values. For solar panels with plastic and without plastic, the maximum power and voltage measured were 4.5 W and 18 V respectively. The experiments were conducted at irradiation of 225 W/m^2 and 301 W/m^2, where the curves for all cases were quiet close to each other. On the other hand, the experiment which was conducted at irradiation of 340 W/m^2 showed that the curve for plastic dusted with talcum powder has a significant difference compared to other three conditions.

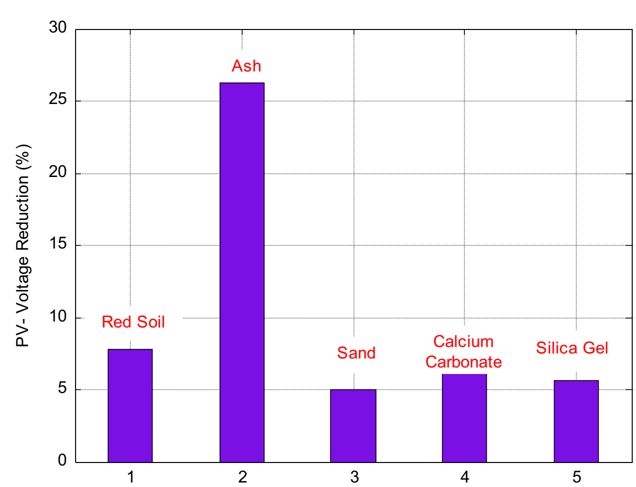

Fig. 9. Decrease in PV voltage due to different types of dust [17].

Table 4
Peak power for different conditions on the PV panel [35].

Condition	Peak power (W)		
	225 W/m^2	301 W/m^2	340 W/m^2
No plastic	4.25	4.12	3.62
Clean plastic	4.25	3.75	3.16
Mud	3.48	3.43	3.49
Talcum	3.55	3.22	1.73

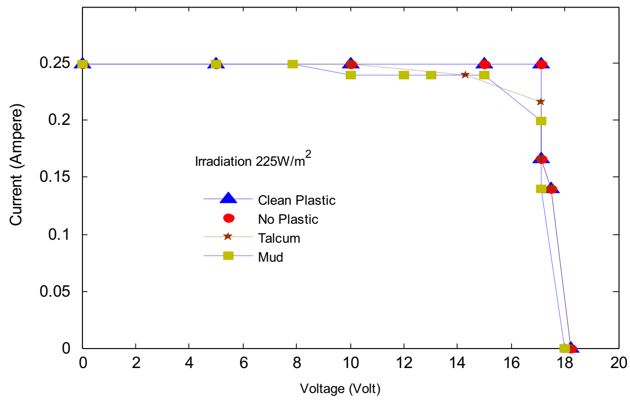

Fig. 10. *I–V* characteristic for irradiation of 225 W/m^2 [35].

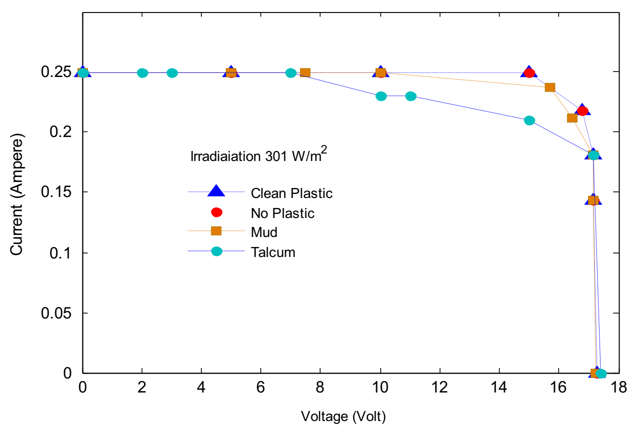

Fig. 11. *I–V* characteristic for irradiation of 301 W/m^2 [35].

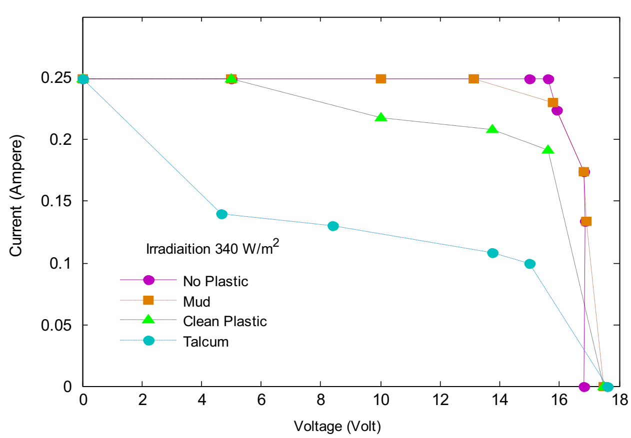

Fig. 12. *I–V* characteristic for irradiation of 340 W/m^2 [35].

Jiang et al. [36] have studied the effect of air borne dust on three types of PV modules namely: (1) monocrystalline (2) polycrystalline and (3) amorphous silicon. The parameters of PV modules are given in Table 5. In this study, a fine test dust (ISO 12103-1 A2, Powder Technology Inc.) was used to simulate the natural dust pollution. The effects of accumulation dust density for different types of PV modules are given in Fig. 13. From Fig. 13 according to the results the dust pollution has a major influence on PV modules when the density of dust deposition increases from 0 to 22 gm^2, and the reduction of output efficiency increases from 0% to 26%. The drop in efficiency has a linear correlation with dust deposition, and the difference caused by cell type is unclear. It was found that the effect of dust on the short circuit current output was significant. The short circuit current *Is* reduced from 100% to 78% of its maximum, and also reduction of the voltage was observed. The maximum reduction of open circuit voltage *Voc* is about 6%.

Table 5
Parameters of the PV module [36].

Module	Cell type	Surface material	Size (mm^2)
1	Monocrystalline silicon	White glass	125 × 125
2	Polycrystalline silicon	Epoxy	125 × 125
3	Amorphous silicon	White glass	125 × 180

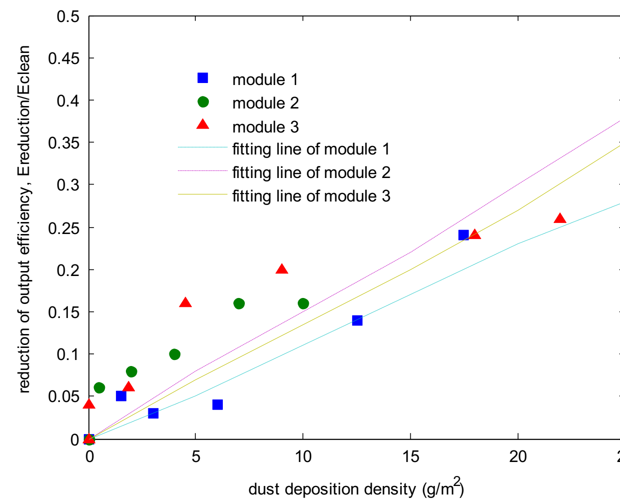

Fig. 13. Variation of output efficiency reduction for different dust depositions [36].

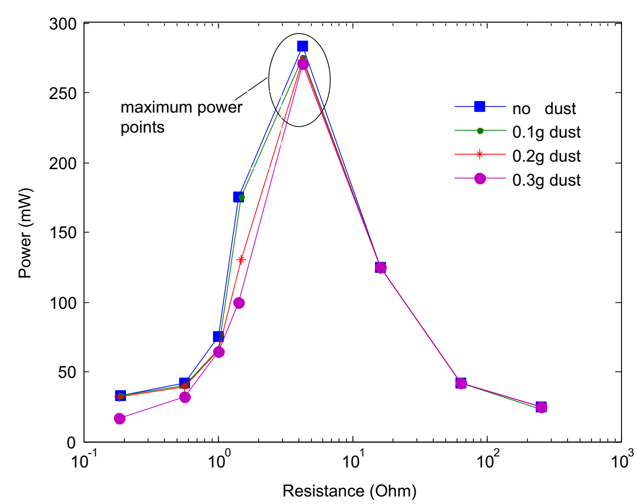

Fig. 14. Change in maximum power point for different amounts of dust deposition [37].

Kumar et al. [37]studied the impact of soiling and dust on the energy performance of PV established by experimental measurements. They used one type of dust clay (bentonite) to examine the effect of dust. With 0.1 g of clay cover, they found that the maximum power of PV panel was 272 mW. By adding more clay, 0.2 g and 0.3 g of clay accumulation, on the panel, the maximum power output of 255 mW and 241 mW respectively was obtained, at constant load of 10 Ω. Figs. 14 and 15 graphically show the outcomes achieved from experiments in the form of current–voltage and power versus load resistance curves.

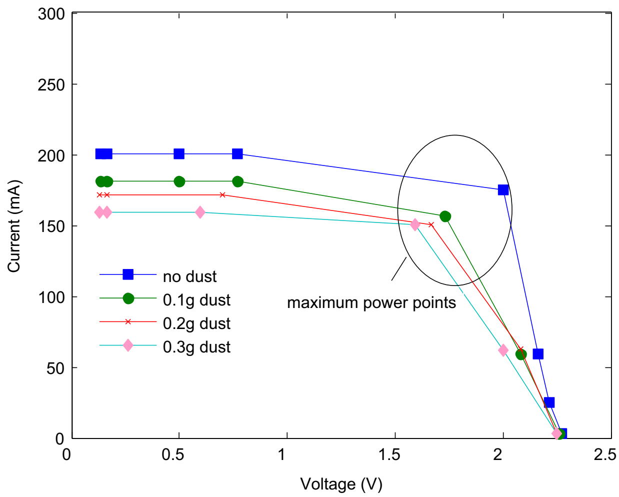

Fig. 15. *I–V* curve for different amounts of dust deposition [37].

In Belgium, Appels et al. [38]studied the relation between the reduction in transmittance and in output power, using two different types of solar panels (a Sanyo HIP-210 NKHE1 and Eurosolare PL160). They used different types of dust, sand (250 μm), clay (68 μm) and cement (10 μm) to coat them. The *I–V* curve was recorded for different amounts of deposited dust and the reduction of maximum power was calculated. It was found that the constant power loss was between 3% and 4% for the ideal tilt angle and steady rainfall.

In Baghdad the capital of Iraq, the effect of dust on performance of PV Street lighting had been studied by Al-Ammri et al. [39]. A sample of deposited dust on the surface of the solar panel at a height of 26 m was examined by a microscope at 100 × magnification and also samples were tested using an XRD-6000 device. The chemical composition was a mixture of SiO_2, $CaCO_3$, Gibson ($CaSO_4$, $2H_2O$), Dolomite (CaMg $(CO_3)_2$), Anorhite ($CaAl_2Si_2O_3$), Kaolinite ($Al_2Si_2O_5(OH)_4$); Ti, Cr, Mn, Fe and Cu were also found when the sample was re-tested with an XRF device. The most deposited dust constituents are SiO_2 and $CaCO_3$. The authors claimed that the losses in output power of fixed solar panel at a tilt angle 35° reached 26% for 1 month.

5. Comparison between effects of pollutant types

According to reviewed studies in previous sections it seems that dust pollutants have not been investigated comprehensively; thus there are no clear model characteristics. The nature of soiling and pollutants varies from area to area throughout the world. Places in urban areas and densely populated areas can be expected to have soiling subjected by pollutants found in those environments such as, for example, vehicles emission, particulates form constructions, and airborne particles from coal-fired utility plants [2]. Similarly, agricultural locations might find types from fertilizers, windblown soil, or plant matter while in desert the sand particles dominate. There were few studies which examined the nature of dust pollution, type of dust, chemical composition, and size [5]. Table 1 includes different types of experiments conducted and the following sections focus on the important elements to be taken in consideration.

5.1. Experiments related to natural dust (outdoor)

A few studies evaluated the dust pollution level and composition at the solar location systems during 1940–1990. The authors of reference [5] said: “With the ambiguity in the dust pollution characteristics, it was possible that the conclusions drawn from an assessment of dust accumulation over a 6 months period is also valid for dust accumulation in 6 weeks in highly polluted sites”. Most of the studies focused on the impact of dust on solar system [Hottel], the effect of dust deposition on the transmittance studied by Hegazy [12] and also Mastekbayeva and Kumar [40]. Pavan et al. [41] investigated the effect of soil type on two (1-MW) PV systems and found 6.9% losses with sandy soil and 1% with more compact soil. Ali et al. [42] investigated dust effect on PV performance in Iraq and the authors claimed that Iraqi dust in urban area form a source of pollution by heavy metals derived from three main sources: automobile activities, industrial, and weathered material, via the concentration of Pb, Zn, Cd, Ni and Cr in street and household dust. The main three pollutants are found to be silica (SiO_2), calcium, and magnesium. Limited studies have analyzed the components of the dust. Al-Ammri examined a sample of deposited dust by a microscope and tested it by an XRD-6000 device. It is worth mentioning here that most of the previous studies focused on the effect of dust accumulation regardless of the contents (pollutant types).

5.2. Experiments related to artificial dust (indoor)

El-Shobokshy and Hussein are considered pioneers who studied fully the dust effect on the performance of PV cells. The study was simulated with artificial dust using carbon particulates, cement and limestone. The diameter of particles was 5 μm for carbon, cement (10 μm), and limestone (50, 60, and 80 μm). In another study that included investigations of the impact of dust on the PV performance by Sulaiman et al. [35] artificial dust which comprised mud and talcum were used.

The efficiency of PV systems is reduced implicitly by the deposition of airborne dust pollution. In this context Jiang et al. [36] studied in a laboratory the dust accumulation onto different types of solar PV module using artificial dust to match the natural dust pollution. A fine test dust (ISO 12103-1 A2, Powder Technology Inc.) was used in this study. On the other hand Khatib et al. [17] studied the dust effect on the PV panels (multi-crystalline) performance.

There were many experiments conducted to analyze the effects of air pollutants, including red soil, ash, sand, calcium carbonate, and silica, on generating power. A study on the impact of air pollutions on PV modules also has been conducted by Kaldellis et al. [4,15]. The experiments were completely simulated with artificial dust, including red soil, limestone and carbonaceous fly-ash particles. According to this study the theoretical model which was developed takes into account the type of the pollutants as well as the mass deposition.

In Tables 6 and 7, a summary of the important points in Table 1 and the discussion in the previous sections about the different types of pollutants is given. Table 6 shows the types of pollutants that are studied individually in several different countries such as carbon, cement, limestone, etc. Also, the combined effect of each pollutant that reduces the performance of PV panel is presented. The most important deduction from this table is that there is no mathematical model applicable for all the pollutants found in literature. But there are a few mathematical models representing specific and particular cases. Researchers proved that other elements also constituted the dust as shown in Table 7. This leads us to say that there is an urgent need to have a model which can be used to simulate effects of dust regardless of the contents (pollutant types).

6. Discussions and conclusions

This paper summarizes the research relating to types of dust pollution. The paper has examined (1) the position of dust pollutant

Table 6
Summary of selected studied reported of dust pollutant type for the period 1993–present.

Name of pollution	Type of pollution		Country of study	Most effected parameter	Mathematical Model
Carbon	Artificial		K.Sudia [33]	*I–V*	
Cement	Artificial	Natural	K.Sudia [33], Belgium [29]	FF, I_{sc},	
Limestone	Artificial		K. Sudia [33]	*P*	
Ash	Artificial		Greece [4] [14], Oman [17]	η	$\Delta\eta_j=\eta_0(1-e^{-Aj\times\Delta Mj})$ [4]
Red soil	Artificial		Greece[4], Oman [17]		
Calcium carbonate	Artificial		Greece[4], Oman [17]		Used for ash, limestone, red soil only
Silica	Artificial		Oman [17]		
Sand	Artificial	Natural	Oman[17], Belgium [38], Iran [24]		
Sand soil		Natural	Italy [41]	*P*	$P=A+BT_{mod}H_i+CH_i+DH_i^2$
Test dust	Artificial		China [36]	η	
Clay	Artificial	Natural	Belgium [38], India [40]		$\eta_{loss}=1-(P_d/P_{nd})$ [40]
Mud	Artificial		Malaysia [35]	*I–V*, peak power, η	
Talcum	Artificial		Malaysia [35]		
Air pollution		Natural	China[32],Iran [29], Mexico [26], Greece [31], Bangladesh [8],	η Tilt angle Energy yield	$P_{max}=aR^bT_{mod}^C$ [26] $\eta=P[q(G_n/G_{n0})+(G_n/G_{n0})^m][1+r(v/v_0)+$ $s(AM/AM_0)+(AM/AM_0)^u]$ [32]
Fine and coarser mode of air born dust	Artificial	Natural	K. Sudia [34], Israel [25]	*I–V*, FF, I_{sc}, P	
Harmattan dust		Natural	Nigeria [28]	P_{max}	
Fine dust		Natural	Algeria [21]	*P* E I	$\eta=-0.0026d^3+0.0326d^2-0.1369d+0.192$ $P=-1.02d^3+12.09d^2-47.516d+63.486$ $I=-0.1008d^3+1.1168d^2-4.0824d+5.202$
Iron dust		Natural	Switzerland [22]	*I–V*, P_{max}	

Table 7
Selected studies used X-ray diffraction analysis of the polluting material.

Name of pollution	Location/year	Chemical composition
Road dust	Alaska/1995 [23]	Halite (NaCl), chlorite ($MgAl_2(OH)$), dolomite ($CaMg(CO_3)_2$), calcite ($CaCO_3$), feldspar ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$)
Desert dust	Libya /2006 [19]	Halite (NaCl), chlorite ($MgFeAl_2(OH)$, calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), feldspar ($KAlSi_3O_8$), quartz (SiO_2), and albite ($NaAlSi_3O_8$)
Desert dust	Egypt/2006[18]	Quartz silicates (SiO_2), about 75%; and feldspars ($NaAlSi_3O_8$, $KAlSi_3O_8$, $CaAl_2Si_2O_8$) about 20%
City dust	Iraq/2013 [39]	SiO_2, $CaCO_2$, Gibson ($CaSO_4\cdot 2H_2O$), dolomite ($CaMg(CO_3)_2$), Anorthite ($CaAl_2Si_2O_8$), Kaolinite $Al_2Si_2O_5(OH)_4$), Ti, Cr, Mn, Fe and Cu

type problem, (2) the effect of dust pollutant type on PV performance and (3) the effect of pollutant type on current, voltage, efficiency, and power. The dust pollution effect which depends on local location is strongly linked to the pollution of local air of the area where the PV system is installed. So it is found difficult to apply a general model in all cases. Many studies have focused on the effect of dust on the performance of PV panel, but did not deal properly with the type of dust and chemical composition. These points need more study to investigate the impact of dust type on the PV performance. The following points are worth highlighting:

1. In literature it is found that there are more than 17 types of dust pollutant types mentioned in different studies which could be reduced after canceling the repeated types to 15 (carbon, cement, limestone, ash, red soil, calcium carbonate, silica, sand, sand soil, clay, mud, talcum, fine and coarser mode of air born dust, and Harmattan dust).
2. In these 17 types some pollutants have an insignificant percentage so that it could be reduced more.
3. The six pollutants types that have more effect are limestone, ash, red soil, calcium carbonate, silica, and sand.
4. The parameters that have been investigated related to the dust pollutant type are current, voltage, power, and efficiency but there is no study that investigates all these parameters together.
5. Most investigations in literature have focused on artificial dust, with fewer studies on natural dust.
6. Only few studies have models for particular cases and particular parameter (i.e. voltage, current, power or efficiency). Mainly these models are for current, power and/or efficiency. No model is related to voltage.
7. Most studies in literature investigated the effect of pollutant types on one type of PV technologies (mono-crystalline, polycrystalline, amorphous silicon, and thin film)

As a conclusion there is an urgent need to have a general model simulating the effect of dust type on PV performance that takes into consideration different pollutant types and different PV technologies, and simulates the effect on current, voltage, power and efficiency.

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